**Final report CENIIT: Elina Rönnberg, Department of Mathematics, 2016—2021**

# Operations Research Methods for Scheduling and Resource Allocation Problems

## *A summary of the most important scientific results*

Through this project, I have established a platform for research in discrete optimisation for solving industrially relevant large-scale scheduling and resource allocation problems – and this was the main goal in my initial application to CENIIT. Many of the research contributions are based on the design of decomposition methods for solving such problems and I expect to continue with this line of research also after the project has finished. During the final year of the project, I extended the methodological scope to also include so-called learning for optimisation, where machine learning is used to enhance the performance of optimisation methods. To move in this direction was not part of my original plan, but the recent advancements in this area have caught my interest.

The industrial collaborations – including Saab, SJ, and Boliden – have been very enriching and contributed to posing interesting research questions. One common property of the problems addressed together with them is that the optimisation is done repeatedly for a fixed large infrastructure – such as the hardware architecture of an aircraft, a railway network, or a mine – while other aspects or data of the problem are changed. After the project, I intend to focus on developing methods for problems with such property since that can be part of improving resource efficiency in many important areas. An appealing aspect of such research is that it can contribute to reaching the Sustainable Development Goals.

On a more technical level, the scientific results related to decomposition are in the areas Dantzig-Wolfe decomposition, Lagrangian relaxation, column generation and logic-based Benders decomposition. Other methodological contributions are within dynamic programming, decision diagrams for optimisation, metaheuristics, and mathheuristics. Ongoing work include improvements of the generic branch-price-and-cut solver in SCIP (one of the fastest non-commercial solvers, often used in research), acceleration techniques for logic-based Benders decomposition, and learning for discrete optimisation.

## *Degrees and promotions the project has contributed to*

2021 Elina Rönnberg, Associate Professor in Optimisation, Linköping University
2018 Elina Rönnberg, Docent in Optimisation, Linköping University

2021 Emil Karlsson, PhD, Linköping University (Elina Rönnberg main supervisor)
2017 Fred Mayambala, PhD, Makarere University, Uganda (Elina Rönnberg co-supervisor)
2016 Yixin Zhao, PhD, Linköping University (Elina Rönnberg co-supervisor)

## *Industrial connections*

During this project, I have also been part-time employed by Saab (~40%, 2014—2020) to lead an R&D-team focused on scheduling and resource allocation problems for the electronic systems of aircraft. The team included 7 people and had a yearly budget of about 2-3 full-time employees. Parts of this work had synergies with the research in this project. The details about the technical outcome for Saab cannot be disclosed in this report. What can be highlighted, however, is the knowledge carried on by the people in the team at Saab. One of them has gone from being a systems engineer to a research scientist with a PhD in optimisation and another team member, that already had a PhD in theoretical computer science, now also has strong expertise in optimisation and scheduling. In this collaboration, we have created a good environment for joint projects to offer in courses and student

thesis projects, and this benefits both LiU and Saab. Several publications originate from the collaboration with Saab, and they have supported making some of the data open for further research. Furthermore, the code developed in the collaboration is allowed for use in further research and Saab has been part of creating a good software development environment at LiU.

The collaborations with SJ and Boliden were initiated during 2020. The collaboration with Boliden has included a project in a course, a master's thesis, and a joint research application. I have given a commissioned education for about 20 employees at Boliden and the joint work has resulted in a paper currently under review. The topic of this paper is scheduling of the excavation in underground mines. In the collaboration with SJ, funded by KAJT (Branschprogram, Kapacitet i Järnvägstrafiken), we address decision support for railway crew planning. This far, the work has resulted in a shorter course for analysts at SJ, an internal report at SJ to establish a foundation for future work, and one publication. This collaboration also includes IVU, a German IT solutions provider for public transport and railway operators, ITN and, TU Wien.

### *Connections with other CENIIT projects*

The strongest connection is with the former project leader Simin Nadjm-Tehrani, who has been the co-supervisor of Emil Karlsson. Mikael Asplund and I have jointly supervised one student thesis.

### *Contributions to creating a group / research environment*

The research environment in this project included supervision of 4 PhD students (the three graduated, listed above, and Aigerim Saken since 2021) and, in a somewhat non-traditional way, the team at Saab. In the early years of the project, one priority was to improve my international network. The result is both the established collaborations with Günther Raidl (TU Wien) and Stephen J. Maher (University of Exeter) and their groups, and a better network in general. During the last two years, I have extended the local network at LiU and applied for project funding together with colleagues at IDA and ITN. The next step is to extend the group at MAI. Thanks to funding from ELLIIT, I have just initiated the recruitment of an ELLIIT faculty assistant professor in discrete optimisation under uncertainty.

### *The value of the contribution from CENIIT*

The funding has mainly been used to form a research identity and a collaboration network to enable further research and the formation of a group. The research network includes both international colleagues and local groups within LiU. The international network is important for exchange of methodological ideas while the local network is of a more interdisciplinary nature to address interesting applications. A third and equally important part of the network is formed by the industrial partners, and it mainly includes collaborations with Saab, SJ, and Boliden.

Since I have not followed a traditional academic career path, the support from CENIIT was crucial to get a chance to do academic research. This, together with other funding for a PhD student, is what made me stay at Linköping University.

### *Persons funded by the project*

Elina Rönnberg, time for research and travel to extend international network.

### *Student thesis works performed within the project*

*collaboration partners stated within brackets*

Alexander Grgic Sjölin, Filip Andersson. Using maximal feasible subsets of constraints to accelerate a logic-based Benders decomposition for a multiprocessor scheduling problem, ongoing, LiU.
[Saab]

Måns Alskog. *Implemetation of a nearly-linear time approximation algorithm for scheduling*, ongoing, 2022.
[Christiane Schmidt, ITN; Saab]

Emil Lindh and Kim Olsson. *Scheduling of an underground mine by combining logic-based Benders decomposition and a constructive heuristic,* master's thesis, LiU 2021.
[Boliden] **Winner: Award for best Swedish OR master's thesis 2021.**

Jesper Svensson. *Designing a large neighborhood search method to solve a multi-processor avionics scheduling problem, master's thesis,* LiU 2021.
[Saab]

Albin Ryberg. *Optimisation of hauling schedules and passing bay locations in underground mines using a time discrete mathematical model,* master's thesis, LiU 2020.
[Combitech; LKAB].

Julia Jobson. *A column generation approach to scheduling of parallel identical machines,* master's thesis, LiU 2019.

Ariyan Abdulla and Erik Andersson. *Heuristic minimization of data latency in offline scheduling of periodic real-time jobs*, bachelor's thesis, LiU 2018.
[Mikael Asplund, IDA; Arcticus]

David Escher. *Offline Avionics Scheduling Subproblem Using Decomposition Methods: Hybridisation between Constraint Programming and Mixed Integer Programming,* master's thesis, UU 2018.
[Pierre Flener and Justin Pearson, Uppsala University; Saab]

Jessika Boberg. *A comparison of sequencing formulations in a constraint generation procedure for avionics scheduling*, bachelor's thesis LiU 2017.
[Saab]

Max Block. *Pre-Runtime Scheduling of an Avionics System,* master's thesis, UU 2016.
[Pierre Flener and Justin Pearson, Uppsala University; Saab]

### *List of reports that are currently under review, with acknowledgement to CENIIT*

E. Lindh, K. Olsson, and E. Rönnberg. Scheduling of an underground mine by combining logic-based Benders decomposition and a priority-based rolling-horizon approach. Submitted March 2022.

E. Karlsson, E. Rönnberg. Logic-based Benders decomposition with a partial assignment acceleration technique for avionics scheduling. Submitted to Computers & Operations Research May 2021 and resubmitted after making a minor revision in February 2022.

S. J. Maher, E. Rönnberg. Accelerating branch-and-price using a novel pricing scheme for finding high-quality solutions in set covering, packing, and partitioning problems. Submitted December 2021.

### *List of publications, with acknowledgement to CENIIT*

F.F. Oberweger, G.R. Raidl, E. Rönnberg, M. Huber. *A Learning Large Neighborhood Search for the Staff Rerostering Problem*. Accepted long paper for the 19th International Conference on the Integration of Constraint Programming, Artificial Intelligence, and Operations Research, 2022.

M. Horn, J. Maschler, G. Raidl, E. Rönnberg. *A*-based construction of decision diagrams for a prize-collecting scheduling problem*. Computers & Operations Research, 125:105125, 2021. https://doi.org/10.1016/j.cor.2020.105125

E. Karlsson, E. Rönnberg, A. Stenberg, and H. Uppman. *A matheuristic approach to large-scale avionic scheduling*. Annals of Operations Research, 302:425—459, 2021. https://doi.org/10.1007/s10479-020-03608-6

M. Horn, G.R. Raidl, E. Rönnberg. *A* Search for Prize-Collecting Job Sequencing with One Common and Multiple Secondary Resources*. Annals of Operations Research, 302:477—505, 2021. https://doi.org/10.1007/s10479-020-03550-7

E. Karlsson, E. Rönnberg. *Strengthening of feasibility cuts in logic-based Benders decomposition.* In: Stuckey P.J. (eds) Integration of Constraint Programming, Artificial Intelligence, and Operations Research. CPAIOR 2021. Lecture Notes in Computer Science, vol 12735. Springer, Cham. https://doi.org/10.1007/978-3-030-78230-6_3

Y. Zhao, T. Larsson, E. Rönnberg. *An integer programming column generation principle for heuristic search methods*. International Transactions in Operational Research, 27:665—695, 2020.

M. Blikstad, E. Karlsson, T. Lööw, E. Rönnberg. *An optimisation approach for pre-runtime scheduling of tasks and communication in an integrated modular avionic system.* Optimization and Engineering, 19:977—1004, 2018.

Y. Zhao, T. Larsson, E. Rönnberg, P.M. Pardalos. *The Fixed Charge Transportation Problem: A Strong Formulation based on Lagrangian Decomposition and Column Generation.* Global Optimization, 72(3):517—538, 2018.

M. Horn, G. Raidl, E. Rönnberg. An A* Algorithm for Solving a Prize-Collecting Sequencing Problem with One Common and Multiple Secondary Resources and Time Windows. In E. K. Burke, L. Di Gaspero, B. McCollum, N. Musliu, E. Özcan (eds.) PATAT 2018: Proceedings of the 12th International Conference of the Practice and Theory of Automated Timetabling, pp. 235—256.

E. Karlsson, E. Rönnberg, A. Stenberg, H. Uppman. Heuristic enhancements of a constraint generation procedure for scheduling of avionic systems. In E. K. Burke, L. Di Gaspero, B. McCollum, N. Musliu, E. Özcan (eds.) PATAT 2018: Proceedings of the 12th International Conference of the Practice and Theory of Automated Timetabling, pp. 417—419.

G. Raidl, E. Rönnberg, J. Maschler, M. Horn. An A*-Based Algorithm to Determine More Efficient Multivalued Decision Diagrams for a Prize-Collecting Sequencing Problem. Poster at CPAIOR 2018.

E. Rönnberg. Co-allocation of communication messages in an integrated modular avionic system. In N. Kliewer, J. F. Ehmke, R. Borndörfer (eds.) Operations Research Proceedings 2017, pp.459-465. Springer International Publishing, Cham, 2018.

E. Karlsson, E. Rönnberg. Explicit modelling of multiple intervals in a constraint generation procedure for multiprocessor scheduling. In N. Kliewer, J. F. Ehmke, R. Borndörfer (eds.) Operations Research Proceedings 2017, pp.567-572. Springer International Publishing, Cham, 2018.

M. Blikstad, E. Karlsson, T. Lööw, E. Rönnberg. A constraint generation procedure for pre-runtime scheduling of integrated modular avionic systems. Proceedings of the 13th Workshop on Models and Algorithms for Planning and Scheduling Problems, 2017.

Y. Zhao, T. Larsson, E. Rönnberg. A large neighbourhood search principle for column-oriented models: theoretical derivation and example applications. Matheuristics 2016: Proceedings of the Sixth International Workshop on Model-based Metaheuristics, 2016.

F. Mayambala, E. Rönnberg, T. Larsson. Tight Upper Bounds on the Cardinality Constrained Mean-Variance Portfolio Optimization Problem Using Truncated Eigendecomposition. Operations Research Proceedings 2014, 385-392, 2016.